USAFETAC/PR-91/004

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A SMOOTHING ALGORITHM FOR UPPER-AIR SOUNDINGS

by

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FEBRUARY 1991

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USAF
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Scott Air Force Base, Illinois, 62225-5438

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REPORT DOCUMENTATION PAGE

2. Report Date: February 1991

3. Report Type: Project Report

4. Title: A Smoothing Algorithm for Upper-Air Soundings

6. Author: Capt Gregory J. Reding

7. Performing Organization Name and Address: USAF Environmental Technical Applications Center (USAFETAC/DNO), Scott AFB, IL 62225-5438

8. Performing Organization Report Number: USAFETAC/PR-91/004

12. Distribution/Availability Statement: Approved for public release; distribution is unlimited.

13. Abstract: This report describes the development of a filtering algorithm for smoothing vertical traces of temperature, pressure and density through the atmosphere. An overlapping mean method employing an exponential weighting function was applied over several adjacent levels to calculate a smoothed value for the required point. The exponential function was chosen because it decreases symmetrically from a central value and easily incorporates a variable bandwidth; this lets users smooth profiles to the desired resolution. Upper-air data needs to be interpolated to evenly-spaced intervals in the vertical prior to program execution; if it is not, resulting profiles will not be hydrostatically consistent. Based on spectral analyis of samples from two test sites, no noise was introduced into the smoothed profiles.

14. Subject Terms: WEATHER, CLIMATOLOGY, STATISTICAL DATA, UPPER ATMOSPHERE, TEMPERATURE, PRESSURE, DENSITY, STATISTICAL ANALYSIS, MATHEMATICAL FILTERS, SMOOTHING

15. Number of Pages: 23

17. Security Classification of Report: Unclassified

18. Security Classification of this Page: Unclassified

19. Security Classification of Abstract: Unclassified

20. Limitation of Abstract: UL

Standard Form 298

PREFACE

In response to USAFETAC Interbranch Tasking (IBT) #90082901 (from ECS), DNO created an algorithm (DNSMOOTH) for smoothing upper-air soundings. The ECS tasking was in response to a support assistance request (SAR) from the HQ Air Weather Service Directorate of Special Projects (AWS/XTJ). The SAR asked ECS to determine the accuracy of a smoothed upper-air profile as a function of resolution of the smoothed profile. DNO project analyst was Capt Gregory J. Reding.

In its IBT, ECS asked DNO to develop a computer algorithm for smoothing a series of temperature, pressure, and density values from upper-air soundings. In its SAR, AWS/XTJ asked that the software be capable of smoothing to a resolution specified by the user prior to program execution so that any given sounding could be smoothed to one of several bandwidths (see 3.3, this report, for a discussion of bandwidth). The AWS-requested feature was incorporated in the software design.

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FIGURES

1. INTRODUCTION.

1.1 DNSMOOTH Explained. The DNSMOOTH program was designed to produce filtered, or smoothed, profiles of upper-air temperature, pressure, and density values for a given period of record (POR). DNSMOOTH uses an "overlapping mean" technique (Panofsky and Brier, 1968). Smoothed values of temperature, pressure, and density are computed from weighted means of the respective variables in the input sounding. Weighted means are computed for data centered on each value in the series. Weighting values decrease exponentially as the distance from this central value increases.

1.2 Input Sounding Interpolation Required. This smoothing method requires that input soundings be interpolated to *regularly* spaced intervals in the vertical. If *irregularly* spaced data is smoothed, a non-hydrostatic atmosphere results, despite the fact that individual sequences of temperature, pressure, and density values are correctly smoothed mathematically.

1.3 Unwanted Noise. Because the "overlapping mean" filtering method has the potential to introduce unwanted noise into the smoothed data, sample soundings (from Wallops Island, VA, and White Sands Missile Range, NM) and their smoothed profiles were subjected to spectral analysis. No unwanted periodicities (noise) were found.

2. DATA

2.1 Test Site Data. Although USAFETAC/ECS intended to eventually to use DNSMOOTH on a number of unspecified sites in the U.S. and USSR, they identified two test sites in the U.S.; these were:

Site	Block Station Number	Latitude	Longitude	Elevation
Wallops Island, VA	724020	37° 51′ N	75° 29′ W	3 meters
White Sands Missile Range, NM	722690	32° 23′ N	106° 29′ W	1,244 meters

2.2 Sounding Files. Upper-air data from 1978 to 1988 was used from each of these stations. Pre-1978 soundings were not used because they included too much missing data. USAFETAC/ECA read the data from tape using ECAUARDR, the standard program for retrieving upper-air data. The sounding files consist of:

Block Station Number (6-digit)

Year (2-digit; (e.g., 78)

Month (2-digit numeric; e.g., 01)

Day (2-digit numeric; e.g., 12)

Hour (2-digit numeric; e.g., 23)

Station elevation (whole meters)

Height of a data level (whole meters)

Temperature at a data level (degrees Celsius)

Pressure at a data level (millibars)

Density at a data level (grams per cubic meter)

3. METHODOLOGY

3.1 Overlapping Mean Smoothing Method. Smoothing, a form of statistical filter, produces a data series from which fluctuations or irregularities have been removed or reduced. Statistical filters usually consist of a series of normalized weights (fractional values) that are multiplied by the series value and summed to obtain the filtered variable (see Equation 1). In this application, a weighted, normalized mean is computed for each new level in the series. Since data from several levels of the input are used to compute each new level of filtered data, there is considerable overlap in input values (Panofsky and Brier, 1968). For this reason, the scheme is referred to as an "overlapping mean" method. Weighted, normalized means are computed with this equation:

$$m_w = \frac{\sum_i (w_i * n_i)}{\sum_i (w_i)} \qquad (1)$$

where

m_w = value of the weighted mean.

w_i = value of the weighting factor at a particular level.

n_i = value of the variable at a particular level.

3.2 The Weighting Function. In a weighted average, data points in a series are weighted according to their distance from the central point. The weight is calculated as a function of the distance between levels of the input observation and the output point. The developed function is:

$$w = e^{-\left[\frac{d}{(0.5*B)}\right]^2} \qquad (2)$$

where

d = the distance an observation in the series is away from the central value.

B = the bandwidth used in the smoothing, or the window of influence over which the weighted mean is calculated. Also known as "resolution."

w = the value of the weight at a distance (d) from the central value. In equation 1, w_i is the value of w for a particular pair of points (input and smoothed).

e = the base of the natural logarithm (2.78128...). It is raised to the given power.

The value of the weights equal 1.00 at the central point and decrease smoothly and symmetrically outward; the closer a value is to the central point, the more influence over the weighted average it has.

3.3 The Concept of Bandwidth. This overlapping mean filter erases small scale irregularities from a series of data. In this case, vertical traces of temperature, pressure, and density are smoothed. The filter's bandwidth determines the scale of fluctuations removed from the base signal by controlling the number of data points included in the calculation of the weighted averages. Since a small bandwidth uses only a few close points, small-scale features are the only ones averaged out. Conversely, a larger bandwidth allows points farther away from the central value to influence the weighted average, and larger-scale features are smoothed. The bandwidth is also known as the "resolution" of the filter--the smaller the resolution, the smaller the scale of features that can be smoothed. In this algorithm, data within one-half a bandwidth above and below the central point is included in the weighted average, but users can select any bandwidth they need.

4. PROGRAM FEATURES

4.1 Language. DNSMOOTH was written in SAS®, a language with several advantages over FORTRAN, including these:

•USAFETAC-developed SAS software can read files of upper-air soundings on disk quickly. It can create SAS permanent data sets that are easier to manipulate than regular partitioned data sets required for FORTRAN.

•USAFETAC/ECS performs further analysis on the smoothed soundings; these analyses are made easier when soundings are processed and output to SAS data sets rather than to another format that would require additional user programming.

•SAS contains several canned procedures that are particularly useful in calculating weighted averages and production of spectral analyses. The SAS MEANS procedure allows rapid computations of sums of data for identical values of year, month, day, hour, and level in the vertical. The SAS SPECTRA procedure performs spectral analysis of a data series without having to develop and code such a routine. As noted in 1.3, spectral analysis was used to quality control the smoothed data and to ensure that filtering did not introduce unwanted periodicities, or "noise."

Note: SAS is a registered trademark of SAS Institute, Inc.

4.2 Preparations.

4.2.1 Interpolated Input Soundings. Before smoothing can begin, soundings must be interpolated to regularly spaced intervals in the vertical. It was shown empirically that when soundings containing unevenly spaced data (for instance, a sounding data set that contained only mandatory and/or significant data levels) were smoothed with this program, the atmosphere described by the smoothed profiles of temperature, pressure, and density was hydrostatically inconsistent even though the traces of individual variables were correctly smoothed mathematically. This was because of the way the smoothing algorithm handles large gaps in a series of data. For example, there might be a situation in which, for a given bandwidth, the same group of data points are used to compute the weighted averages for several adjacent levels of the smoothed output sounding--see the example soundings in Figures 1 and 2. In both cases, the input data was the same, but it was used to compute the averaged values of temperature for several adjacent levels in the vertical. Only the weights for each level differed slightly. Several irregularities can result from this situation. In Figure 1, the resultant temperature of -11.69° C at the 500-meter level was incorrectly biased toward the cold when compared to input data from about the same height (only -10° C at at 545 meters). The opposite occurs in Figure 2 at the 700-meter level--the smoothed temperature of -12.15° C is biased toward the warm compared to -15° C at 745 meters in the source sounding.

RAW SOUNDING		SMOOTHED PROFILE	
Height (m)	Temperature (°C)	Height (m)	Temperature (°C)
097	+06	100	+6.00
200	*	200	+5.33
300	*	300	-4.13
400	*	400	-10.33
545	-10	***500***	***-11.69***
690	-11	600	-11.82
745	-15	700	-12.15
800	*	800	-12.45
900	*	900	-21.00
1,000	*	1,000	-30.31
1,127	-40	1,100	-40.00

Figure 1. An example of 600-meter bandwidth used to smooth raw data with gaps in the series, for the 500-meter level. Note that the same values of temperature were used to compute a weighted average of temperature for the 500-meter level as were used for several adjacent levels. While correct mathematically, this produces a profile that, when combined similarly smoothed pressure and density profiles, describes a non-hydrostatic atmosphere. An asterisk (*) represents missing data.

RAW SOUNDING		SMOOTHED PROFILE	
Height (m)	Temperature (°C)	Height (m)	Temperature (°C)
097	+06	100	+6.00
200	*	200	+5.33
300	*	300	-4.13
400	*	400	-10.33
545	-10	500	-11.69
690	-11	600	-11.82
745	-15	***700***	***-12.15***
800	*	800	-12.45
900	*	900	-21.00
1,000	*	1,000	-30.31
1,127	-40	1,100	-40.00

Figure 2. An example of 600-meter bandwidth used to smooth raw data with gaps in the series, for the 700-meter level. Note that the same input values of temperature used to compute the weighted average of temperature at 500 meters were also used for 700 meters.

In the extreme case, a single data point in the raw data sounding may be used to compute values for several adjacent levels in the smoothed profile, resulting in identical values at each level. The result is incorrect, and particularly unsatisfactory when it occurs in traces of pressure and density. USAFETAC/ECA automatically produced upper-air data in an interpolated format by running its ECAUARDR program, the code that reads upper-air data from tape and writes it to disk.

4.2.2 User-Supplied Variables. Before running DNSMOOTH, several variables in the associated job control language (JCL) must be set. These variables, listed below, select the upper-air site for which soundings are to be smoothed, the bandwidth of the smoothing, the lowest and highest levels of the filtered profiles, and the interval between levels.

- ZSTART Lowest level of the smoothed output profiles, entered in meters.
- ZSTOP Highest level of the smoothed output profiles, entered in meters.
- INTRVL Interval between levels in the smoothed output profiles, entered in meters.
- BWIDTH Bandwidth used in the smoothing process, entered in meters.
- BLKSTA Block Station Number of the upper-air site of interest. Files of upper-air data for this project were stored on disk and identified by block station number. This variable allows selection from one of several upper-air sites' data files for processing.

5. TESTING AND VERIFICATION.

Smoothed output profiles were tested to ensure that (1) the smoothed profiles were hydrostatically consistent, and (2) extraneous fluctuations had not been introduced into the output profile by the smoothing process.

5.1 Test for Hydrostatic Atmosphere. In order to verify that an atmosphere described by the smoothed traces of temperature, pressure, and density is hydrostatic, values of temperature and pressure at the top and bottom of two 1,000-meter layers of a smoothed profile were entered into the hypsometric equation (Byers, 1974), an integration of the hydrostatic equation:

$$z_2 - z_1 = \frac{R * \overline{T}_v}{g} \left[ln(p_1) \; - ln(p_2)\right] \tag{3}$$

where

z_2 = height of the top of the layer (geopotential meters)

z_1 = height of the bottom of the layer (geopotential meters)

R = gas constant for dry air (Joules kg^{-1} K^{-1})

$\overline{T}_v$ = mean virtual temperature (K) of the layer

g = acceleration due to gravity (m s^{-2})

p_1 = pressure at the bottom of tne layer (mb)

p_2 = pressure at the top of the layer (mb)

It was assumed that the soundings were essentially dry, and that the mean virtual temperature of the layer was approximately equal to the layer's mean temperature:

$$z_2 - z_1 = \frac{R * \overline{T}}{g} \, ln\left(\frac{p_1}{p_2}\right) \tag{4}$$

where

$\overline{T}$ = mean temperature (K) of the layer

Using equation 4, 1200Z soundings for 12 January 1978 at White Sands Missile Range, NM, and Wallops Island, VA, were tested. Temperature and pressure were taken from the bottoms and tops of 1,000-meter layers with bases at 4,000 and 10,000 meters. Two profiles from each site were checked; one that had been smoothed with a 2,000-meter bandwidth, the other with a 4,000-meter bandwidth. This test was intended to show if a change in bandwidth affected the hydrostatic assumption of the output profiles. Since the layer between these levels was 1,000 meters thick, temperature and pressure at the bottom and top of the layers were entered into the hypsometric equation and the computed layer depth compared to 1,000 meters. The percent error of the layer depth from 1,000 meters was as a measure of how close the atmosphere was to hydrostatic. Figures 3 and 4 show the results of these calculations.

WALLOPS ISLAND

height (m)	temperature (°C)	pressure (mb)	calculated layer thickness (m)	% error from 1,000 m
4,000	-8.96	622.64		
			996.78	0.32
5,000	-15.23	546.52		
10,000	-54.25	267.62		
			998.08	0.19
11,000	-57.78	228.74		

WHITE SANDS

height (m)	temperature (°C)	pressure (mb)	calculated layer thickness (m)	% error from 1,000 m
4,000	-14.16	615.80		
			998.48	0.15
5,000	-20.97	538.89		
10,000	-49.23	262.49		
			999.32	0.07
11,000	-51.82	225.18		

Figure 3. Percent error from hydrostatic atmosphere for smoothed profiles, Wallops Island and White Sands, smoothing bandwidth 2,000 meters.

WALLOPS ISLAND			calculated	
			layer	% error
height (m)	temperature (°C)	pressure (mb)	thickness (m)	from 1,000 m
4,000	-8.96	622.64		
			995.56	0.44
5,000	-15.23	546.52		
10,000	-54.25	267.62		
			995.10	0.49
11,000	-57.78	228.74		
WHITE SANDS			**calculated**	
			layer	**% error**
height (m)	**temperature (°C)**	**pressure (mb)**	**thickness (m)**	**from 1,000 m**
4,000	-13.81	619.68		
			995.26	0.47
5,000	-20.82	542.59		
10,000	-48.23	265.02		
			996.61	0.34
11,000	-51.59	227.54		

Figure 4. Percent error from hydrostatic atmosphere for smoothed profiles, Wallops Island and White Sands, smoothing bandwidth 4,000 meters.

Although increasing the bandwidth raised the percent error slightly, it was still less than 0.5 percent. Since the errors in all these cases were quite low, we concluded that the profiles smoothed by DNSMOOTH satisfied the hydrostatic equation, provided that soundings interpolated to regularly-spaced intervals were used as input.

5.2 Spectral Analysis. Smoothing methods have the potential for inducing unwanted structures into the smoothed data--features that were not inherent to the original data series but that can be detected using spectral analysis of the smoothed data. Spectral analysis shows the contributions of oscillations with various frequencies to the variance of the time series itself (Panofsky and Brier, 1968). If any periodic feature were introduced into the smoothed data, it would show up in a spectral analysis as a peak in the "energy" spectrum of the smoothed data that was absent in the original spectrum. SAS's SPECTRA procedure was used for spectral analysis of smoothed profiles to look for any unwanted periodicities that would point to a flaw in the smoothing procedure. Figure 5 is a plot of the energy spectrum analysis from a temperature sounding interpolated to 1,000-meter intervals from Wallops Island. Figures 5 and 6 show the spectra for the resulting profiles smoothed with bandwidths of 2,000 and 5,000 meters, respectively.

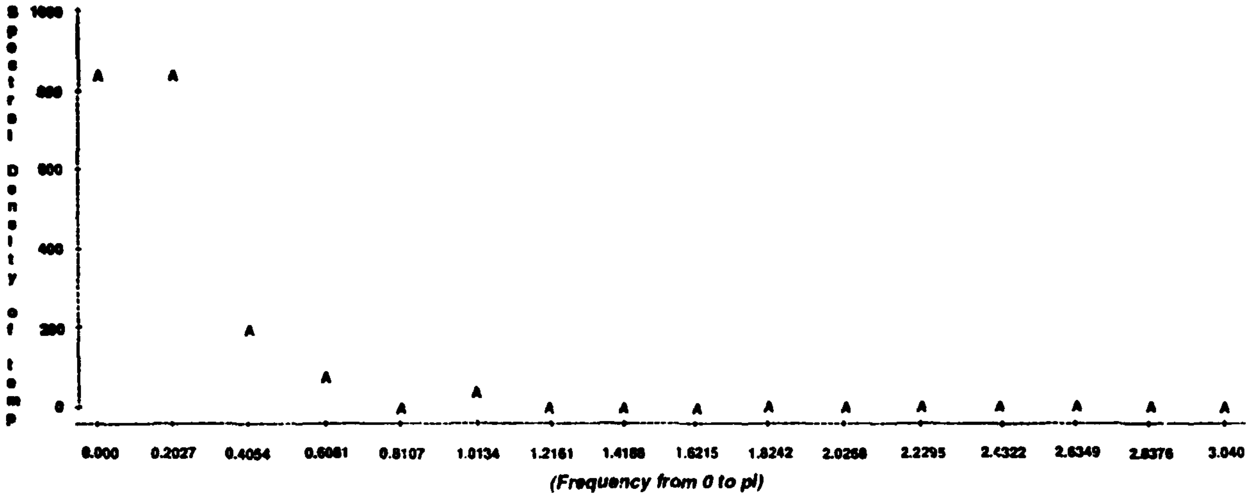

Figure 5. Frequency spectrum plot of the components comprising a temperature sounding from data interpolated to 1,000-meter intervals, Wallops Island VA, 24 January 1978, 1200Z.

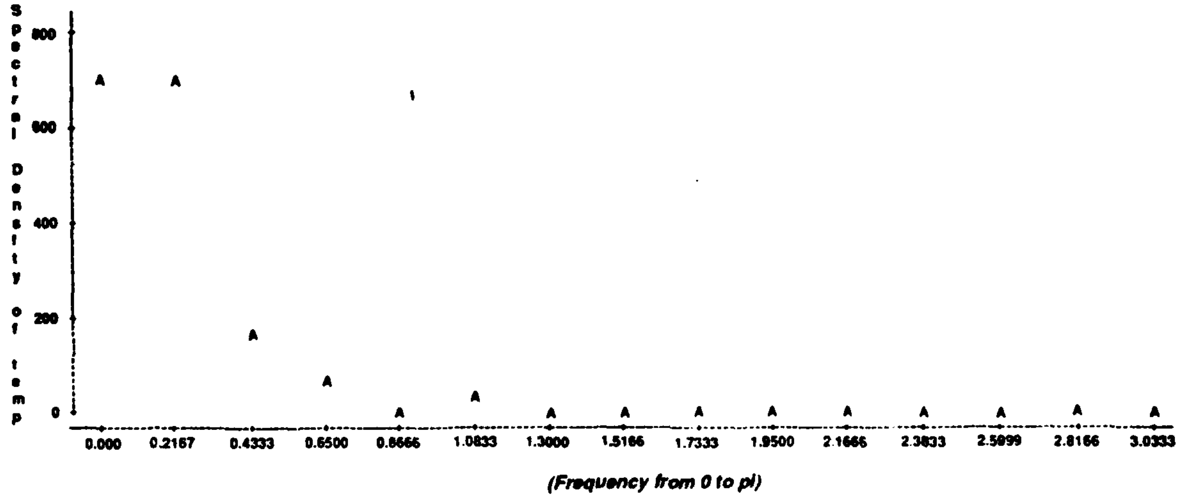

Figure 6. Frequency spectrum plot of the components comprising a temperature profile smoothed with a 2,000-meter bandwidth, Wallops Island VA, 24 January 1978, 1200Z.

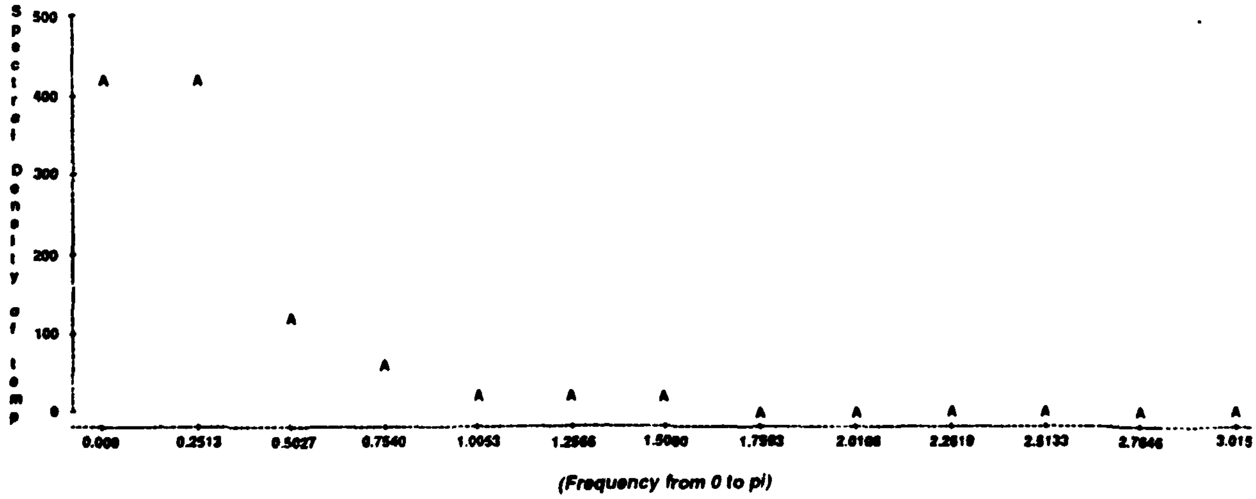

Figure 7. Frequency spectrum plot of the components comprising a temperature profile smoothed with a 5,000-meter bandwidth, Wallops Island VA, 24 January 1978, 1200Z.

When comparing interpolated and smoothed soundings' spectra, it was apparent that no energy peaks developed as a result of the filtering. In the smoothed soundings, a distinct decrease in amplitude and spreading out of the major peak (related to the primary frequency of the temperature profile from the surface through the stratosphere--Figure 6, frequency = 0.2027), is seen as the smoothing bandwidth increases from 2,000 to 5,000 meters. This is to be expected as the curve is averaged over a greater vertical extent and larger scale fluctuations are washed out. For this sounding, it is evident that the smoothing process did not introduce undesirable oscillations in the energy spectra. Spectral analyses performed on a series of pressure and density values from Wallops Island, and of temperature, pressure, and density values from White Sands, showed similar performance. It was concluded that the smoothing program operates correctly without introducing incidental oscillations into the smoothed profiles.

6. PROGRAM PERFORMANCE NOTES

6.1 Missing Data at Top and Bottom of Smoothed Profiles. If any level of a profile is closer than one-half a bandwidth from the bottom or top of the input sounding, the smoothed values of temperature, pressure, and density for that level are deliberately set to "missing" in the code. If this is not done, there would be a bias because a full bandwidth of data was not used in computating weighted averages for that level.

6.2 Use of Interpolated Soundings as Input. If a smoothed profile that satisfies the hydrostatic equation is required, the input soundings must first be interpolated to regularly spaced intervals in the vertical. If non-interpolated, or "raw" data is used in the smoothing routine, resulting profiles might describe an "impossible" atmosphere.

6.3 Limits on Bandwidth Size. To avoid a trivial solution, the bandwidth should never be less than twice the interval between levels in the input soundings. If the bandwidth is less than or equal to the interval between levels, no smoothing will occur, and the smoothed output profile will be identical to the input.

6.4 Limits on Sizes of Input and Output Data Sets.

6.4.1 Input Data Set. When deciding on the sounding interpolation interval, the amount of data used must be considered. A data set interpolated from a standard USAFETAC 10-year POR, depending on the interval chosen, may include hundreds of thousands of records. When coupled with internal SAS processes that generate even larger temporary data sets, the system internal memory allocated for SAS processes may be exceeded, and the program will not run.

6.4.2 Output Data Set. Caution should also be used in selecting the dimensions of the output profiles; that is, the tops and bottoms of the profiles and the intervals between levels. A 10-year output data set designed with a maximum height of 30,000 meters and 250-meter separation between levels will generate an internal SAS work data set of over 2 million records. This will exceed available internal memory, and the program will not run. For 10 years of upper-air data, USAFETAC recommends an interval of not less than 500 meters between layers for an output profile 30,000 meters in height.

7. CONCLUSIONS

DNSMOOTH will smooth (or filter) an entire POR of upper-air soundings to a user-specified resolution. The user also controls site selection, the height of the top and bottom of the smoothed profiles, the interval between levels, and the bandwidth used to filter the input soundings. If sounding data that is interpolated to regularly spaced intervals in the vertical is input to DNSMOOTH, the resulting smoothed profiles are hydrostatically consistent. On the other hand, raw, uninterpolated soundings result in smoothed profiles that describe a non-hydrostatic atmosphere. The smoothing method chosen, one of overlapping weighted means, does not introduce undesirable features into the smoothed profile, as proved by spectral analysis. Users must use caution in selecting the POR of input data and the interval to which it is interpolated, as well as the final dimensions of the output smoothed profiles, in order to avoid producing working data sets too large for SAS to process on USAFETAC's IBM mainframe computer.

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Panofsky, Hans A., and G. W. Brier, *Some Applications of Statistics to Meteorology,* Pennsylvania State University Press, University Park, 1968.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

B	Bandwidth (used in equation 2)
BLKSTA	Block Station Number, a user-controlled variable
BWIDTH	Bandwidth, a user-controlled variable
d	Vertical distance between a particular data value and the central value, used to compute a weighted mean in equation 2
DNO	Operations Applications Development Section, USAFETAC
DNSMOOTH	Software created by DNO to smooth upper air soundings
e	Base of the natural logarithm
ECA	Systems Support Section, USAFETAC
ECAUARDR	Upper-Air Reader program. Written by ECA to read upper-air data from tape and create a file on disk
ECS	Special Projects Section, USAFETAC
g	Acceleration due to gravity.
INTRVL	Interval between levels in the smoothed output profiles, a user-controlled variable
JCL	Job Control Language. Instructions to the operating system governing execution of a computer program and describing its input and output
MEANS	Software routine within the SAS language that computes various statistics
m_w	Value of a weighted mean
n_i	Value of a variable at a particular level, used to calculate a weighted mean in equation 1
POR	Period of Record. Chronological content of a collection of data
p_1	Pressure at the bottom of a layer of the atmosphere
p_2	Pressure at the top of a layer of the atmosphere
R	Gas constant for dry air
SAS	Statistical Analysis System. Fourth-generation computer language used at USAFETAC
SPECTRA	Software routine within the SAS language that performs spectral analysis
$\bar{T}$	Mean temperature of a layer of the atmosphere
$\bar{T}_v$	Mean virtual temperature of a layer of the atmosphere
w	Value of a weighting factor determined by equation 2
w_i	Value of a weighting factor at a particular level
XTJ	Directorate of Special Projects, Headquarters AWS
ZSTART	Lowest level of the smoothed output profile, a user-controlled variable
ZSTOP	Highest level of the smoothed output profile, a user-controlled variable
z_1	Bottom of a layer of the atmosphere
z_2	Top of a layer of the atmosphere

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OFCM, Suite 900, 6010 Executive Blvd, Rockville, MD 20852 1
NOAA *Library*-EOC4WSC4, Attn: ACQ, 6009 Executive Blvd, Rockville MD 20852 1
NOAA/NESDIS (Attn: Nancy Everson, E/RA22), World Weather Bldg, Rm 703, Washington, DC 20233 1
NOAA/NESDIS (Attn: Capt Taylor), FB #4, Rm 0308, Suitland, MD 20746 1
GL/LY, Hanscom AFB, MA 01731-5000 1
GL Library, Attn: SULLR, Stop 29, Hanscom AFB, MA 01731-5000 1
Atmospheric Sciences Laboratory, Attn: SLCAS-AT-AB, Aberdeen Proving Grounds, MD 21005-5001 1
Atmospheric Sciences Laboratory, Attn: SLCAS-AS-I, White Sands Missile Range, NM 88002-5501 1
Army Missile Command, ATTN: AMSMI-RD-TE-F, Redstone Arsenal, AL 35898-5250 1
Army Missile Command, ATTN: AMST-TC-AM (RE), TCOM Met Team, Redstone Arsenal, AL 35898-8052 1
Commander and Director, U.S. Army CEETL, Attn: GL-AE, Fort Belvoir, VA 22060-5546 1
Technical Library, Dugway Proving Ground, Dugway, UT 84022-5000 1
NCDC Library (D542X2), Federal Building, Asheville, NC 28801-2723 1
NIST Pubs Production, Rm A-405, Admin Bldg, Gaithersburg, MD 20899 1
DTIC-FDAC, Cameron Station, Alexandria, VA 22304-6145 2
AUL/LSE, Maxwell AFB, AL 36112-5564 1
AWSTL, Scott AFB, IL 62225-5438 35